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Comparison of wetland and agriculture drainage as sources of biochemical oxygen demand to the San Joaquin River, California

William T. Stringfellow[a,b,*], *Jeremy S. Hanlon*[b], *Sharon E. Borglin*[a,b], *Nigel W.T. Quinn*[a]

[a] *Lawrence Berkeley National Laboratory, Ecology Department, Earth Sciences Division, 1 Cyclotron Road, MS 70A-3317, Berkeley, CA 94720, United States*

[b] *Environmental Engineering Research Program, School of Engineering & Computer Sciences, 3601 Pacific Avenue, Sears Hall, University of the Pacific, Stockton, CA 95211, United States*

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ABSTRACT

For many years, the San Joaquin River (SJR) has had low dissolved oxygen conditions intermittently during the late summer and early fall. The low dissolved oxygen conditions are impacting critical fish habitat and the SJR is being regulated under a state of California remediation plan that includes the development of a total maximum daily load (TMDL) allocation for oxygen demanding substances. In support of the development of a scientific TMDL allocation, studies are being conducted to characterize water quality in the many tributaries of the SJR. This study identified the sources of biochemical oxygen demand (BOD) in two western tributaries of the SJR, Mud Slough and Salt Slough, and measured the loads of BOD, algae, and ammonia entering the SJR from wetland and agricultural sources.

Mud and Salt Sloughs drain the Grassland Watershed. The watershed contains seasonal wetlands, irrigated farmland, and other agricultural lands. This drainage is under close regulatory scrutiny, because it produces a majority of the selenium and boron entering the SJR. In this study, wetland and irrigated agricultural drainage were sampled separately and a comparison was made to determine differences in water quality. In addition, water entering the study area was compared to water exiting the study area to determine the effect of water use in the region on water quality.

This study demonstrated that BOD loads from the Grassland Watershed to the SJR were proportional to flow during June–October, the most critical time for dissolved oxygen deficits in the lower SJR. This indicates that Mud and Salt Sloughs are not producing more BOD than other tributaries in the region that are not under close regulatory scrutiny. The BOD concentration of wetland drainage is higher than that of agricultural drainage, but the higher agricultural drainage flows result in a higher mass loading of BOD. Wetland flooding and irrigation of crops both had a negative impact on water quality. Algal growth was identified as the major source of BOD in agricultural drainage and locations where BOD control could potentially be implemented were identified.

* *Corresponding author at*: Lawrence Berkeley National Laboratory, Ecology Department, Earth Sciences Division, 1 Cyclotron Road, MS 70A-3317, Berkeley, CA 94720, United States. Tel.: +1 510 486 7903; fax: +1 209 946 2577.
E-mail address: wstringfellow@lbl.gov (W.T. Stringfellow).
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1. Introduction

The dissolved oxygen (DO) concentration in the San Joaquin River (SJR) adjacent to Stockton, CA frequently falls below 5 mg/L between July and October. The DO deficits occur (Fig. 1) where the river changes depth from an average of approximately 3 m to a dredged depth of 10 m. The fall-run of adult Chinook salmon can occur as early as September on this river and dissolved oxygen concentrations less than 6 mg/L are believed to inhibit upstream migration of this species. The regional water quality control board (RWQCB) has set a dissolved oxygen objective of 6 mg/L during September through November and 5 mg/L throughout the rest of the year for this river (Gowdy and Grober, 2003). Oxygen demand is typically referred to, measured, and regulated as biochemical oxygen demand (BOD).

As part of a DO total maximum daily load (TMDL) on the SJR, there is interest in characterizing the generation of oxygen demanding substances throughout the basin. Modeling studies have identified algal biomass (measured as algal pigments) and ammonia as the most significant components of BOD in the low DO areas of the SJR (Gowdy and Grober, 2003). Previous investigations have shown that phytoplankton biomass from the upstream reach are an important source of oxygen demanding materials entering the tidal portion of the SJR (Lehman et al., 2004; Volkmar and Dahlgren, 2006). Tributary sources of BOD entering the river are not well understood.

This study was conducted to identify and characterize sources of oxygen demanding materials entering the river from Mud Slough and Salt Slough, two western tributaries on the SJR. Mud and Salt Sloughs are only two of many tributaries on both the eastside and westside of the SJR potentially contributing BOD to the SJR. The Mud and Salt Slough tributaries are located over 100 km upstream of the low DO area (Fig. 1), however, these tributaries are highly regulated drainages and have been instrumented for measurement of flow at key locations in the watershed, making them a logical

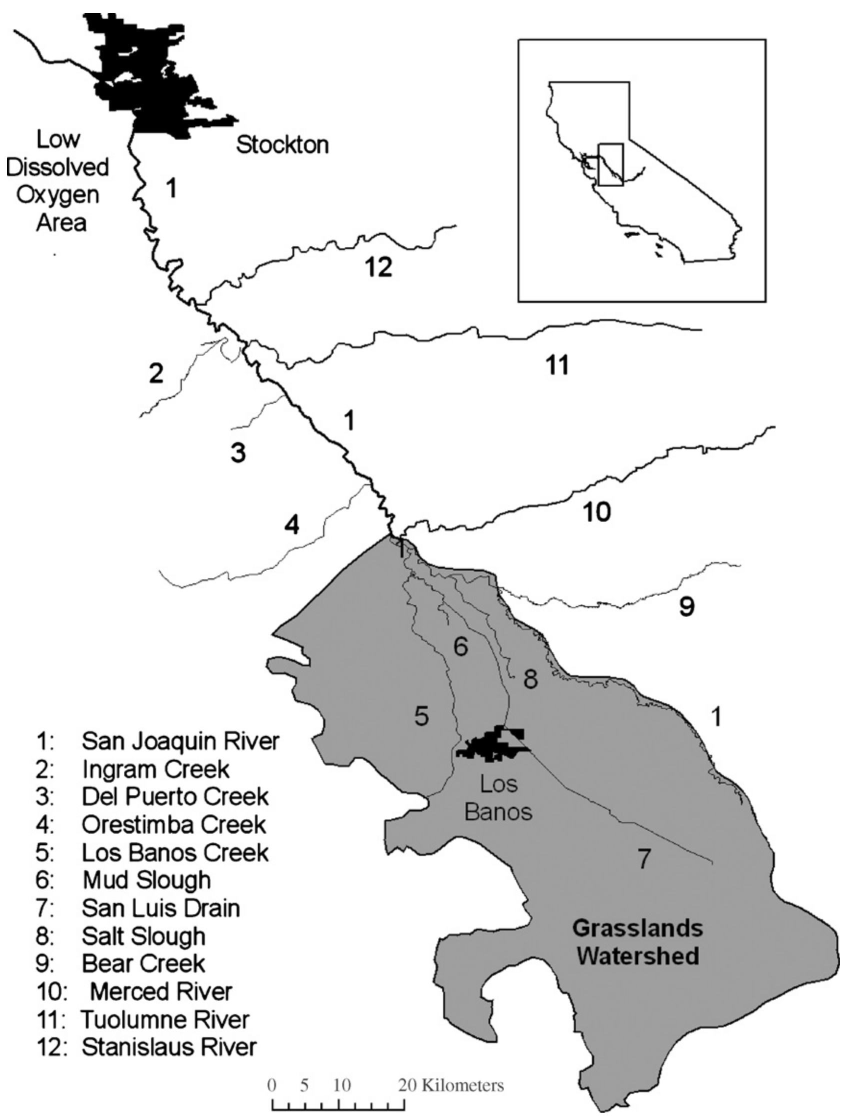

Fig. 1 – Regional map of the lower San Joaquin River drainage showing location of the Grasslands Watershed in relation to the low dissolved oxygen area adjacent to Stockton, CA.

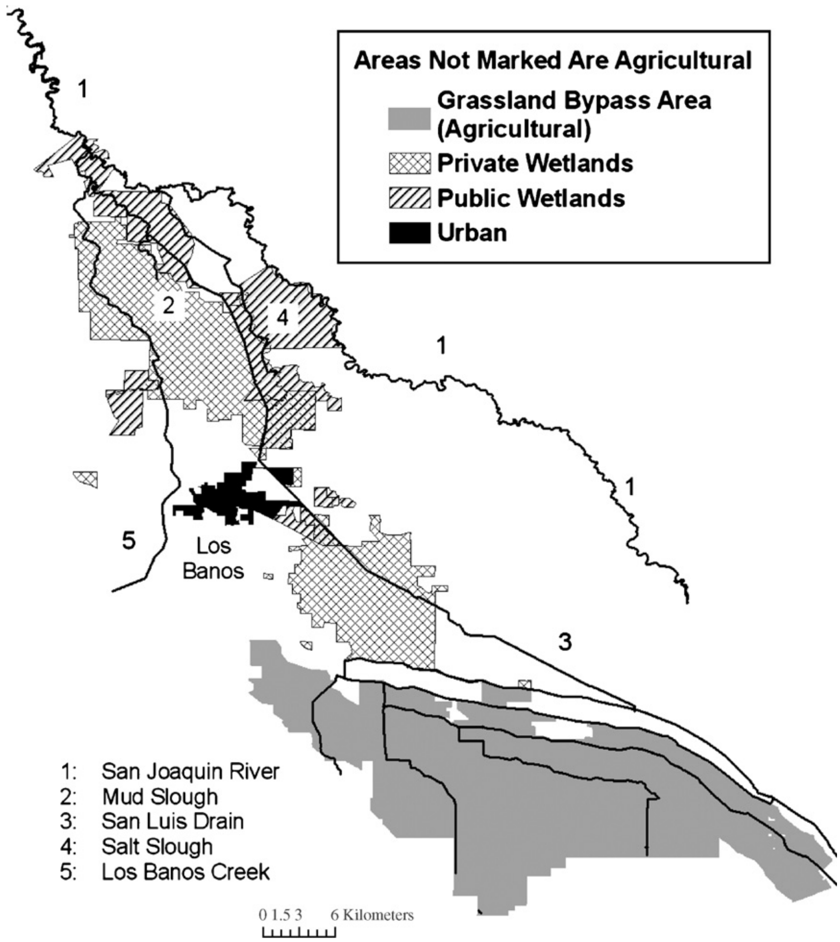

Fig. 2 – Regional map of study area showing location of public and private managed wetlands in the Grassland Watershed. The grassland bypass area is an agricultural area which uses a section of the San Luis drain to convey agricultural drainage past sensitive public and private wetlands.

location for initial investigation of oxygen demand in the SJR basin.

Mud Slough and Salt Slough are the major sources of selenium, boron, salt, and molybdenum in the SJR (Johns and Watkins, 1989). The drainage from Mud and Salt Sloughs accounts for nearly half of the nitrate in the SJR and these tributaries are major sources of pesticide runoff (Dubrovsky et al., 1998; Kratzer et al., 2004). The Salt and Mud Sloughs drainage basin has been a particular focus of regulatory scrutiny since a drainage management project resulted in the accumulation of toxic concentrations of selenium in the Kesterson Reservoir (Benson et al., 1993). Since that time, there has been an on-going effort to reduce discharges of salt and selenium from the region (Chilcott et al., 2000; Quinn et al., 1996). The Salt and Mud Sloughs tributaries are included in a salinity TMDL being developed by the RWQCB (Central Valley Regional Water Quality Control Board, 2004). Given the importance of these tributaries to water quality in the SJR, it is important to investigate BOD in these drainages as well.

Salt and Mud Sloughs drain the Grassland Watershed (Fig. 1). Although this watershed is classified as agricultural, it also includes public and private managed wetlands (Chilcott et al., 2000; Quinn et al., 1996). Managed wetland and agricultural water use in this region are quite different. Agricultural crops are irrigated throughout the summer months and fields may produce drainage throughout the growing season. In the winter, drainage from agricultural lands is largely a function of rainfall (Chilcott et al., 2000). The agricultural drainage in this region is predominately from sub-surface tile drains (Johns and Watkins, 1989; Chilcott et al., 2000), but the tile drainage is collected in unlined surface ditches and eventually routed to two major drainages, Salt Slough and the San Luis drain (SLD) (Figs. 1 and 2).

Water use in managed wetlands is similar in both public and private wetlands. Seasonal wetlands are flooded in the winter and are dry in the summer. Permanent wetlands are flooded throughout the year. In the fall, typically starting in early September, seasonal wetlands are flooded for the winter water-fowl season. During this fall ‘‘flood-up’’ period, previously dry areas are filled with water and permanent wetlands may receive additional water. These management actions typically result in discharge flows from wetland management areas. In the spring discharge or ‘‘draw-down’’ period, water in the seasonal wetlands is drained, leaving seasonal wetland areas dry for the summer. During the summer, seasonal wetlands may be utilized for livestock grazing or planting and may be irrigated, resulting in occasional summer drainage flow. The Central Valley Project Improvement Act allocated additional water deliveries for wildlife habitat, so wetlands in this region typically receive water of the same quality as irrigated agriculture.

Previous studies examining the water quality of agricultural drainage typically did not measured BOD (Ayars et al., 1997; Domagalski et al., 2001; Dubrovsky et al., 1998; Evans et al., 1995; Wesstrom et al., 2001). Tile drains are the predominate source of agricultural drainage in the Grasslands region and tile drainage could be expected to be low in BOD. Agricultural soils have thriving bacterial communities that can degrade labile organic carbon and ammonia. Even irrigation water containing high concentrations of organic carbon and ammonia are characteristically low in BOD after percolation through the soil column (Tanji, 1997).

Drainage from public and private managed wetlands are a more likely source of BOD emissions in this region. Wetlands support large bird populations and plant communities that can contribute ammonia and carbon to the standing water of the wetland. Algae growth can be abundant in wetlands. Most of the wetlands drainage included in this study is surface runoff that has not been filtered through the soil column. Although there are many studies on BOD removal in wetlands receiving wastewater, there are fewer studies evaluating BOD production in wetlands receiving higher quality water (Sundaravadivel and Vigneswaran, 2001; Johnston, 1991). Several studies have examined changes in nutrient concentrations that occur in wetlands and most have found a net removal of nutrients in the wetland (e. g. Johnston, 1991).

The purpose of this study was to investigate sources of oxygen demanding materials in the Salt and Mud Sloughs tributaries of the SJR between June and October 2001. A mass balance approach was used to compare and contrast the wetland and agricultural drainage of the Grassland Watershed and to evaluate the importance of Mud and Salt Sloughs to the total BOD found in the SJR. We also compared drainage to background sampling locations representing water entering the study area to determine the impact of water use in the region on overall water quality.

2. Materials and methods

2.1. Research area description

Mud Slough and Salt Slough are main drainage arteries of the Grassland Watershed, an approximately 260,000 ha area west of the SJR, covering portions of Merced and Fresno counties (Fig. 1). The watershed includes approximately 40,000 ha of wetland habitat and 20,000 ha of urban land, with the balance of land used predominantly for irrigated agriculture. The wetland habitat includes private wetlands that are managed as duck-hunting clubs and publicly owned wetlands that are managed as state wildlife areas and federal wildlife refuges (Fig. 2).

South of a major area of public and private wetlands is approximately 80,000 ha of farmland, organized as the grassland bypass area (Fig. 2). Subsurface agricultural drainage in the grassland bypass area is collected into surface drains and routed to the San Luis drain which conveys this agricultural drainage around sensitive wetlands to Mud Slough (Fig. 2, Chilcott et al., 2000; Quinn et al., 1996).

Figs. 3 and 4 show maps of the project research area. Drainage from the grassland bypass area enters the SLD near Site A, South of Los Banos, and is conveyed north approximately 45 km, past the public and private wetlands, until it discharges just downstream of Site B into Mud Slough (Fig. 3). Volta Wasteway is the major source of water for the private wetlands in the study area (Figs. 3 and 4). The majority of the surface water used for both irrigation and wetland management in the Grassland Watershed is imported from the Sacramento–San Joaquin Delta through the Delta–Mendota Canal (Fig. 3). Crows Landing on the SJR is the location of a flow monitoring station used by regulatory agencies as a monitoring point for water quality in this reach of the SJR (Fig. 3).

2.2. Sample sites

Sample sites were chosen to differentiate wetland and agricultural sources of drainage (Fig. 4). Table 1 lists the name and location of sampling stations discussed in this paper. The sample points used in this study correspond to flow gauging stations operated by the USGS, LBNL or local water agencies (Table 1, Figs. 3 and 4).

The Mud Slough at Gun Club Road monitoring station represents drainage from a large area of private managed wetlands west of Highway 165 (Fig. 4). This station is located on Mud Slough upstream of the confluence of Mud Slough and the SLD. Water is supplied to the private wetlands in the study area via the Volta Wasteway (Figs. 3 and 4). Approximately 60% of the surface flows leaving the private wetlands delineated in Fig. 4 drains through Mud Slough at Gun Club Road. By comparing Volta Wasteway to Mud Slough at Gun Club Road, we can determine the influence of the wetlands on water quality.

The only significant source of agricultural drainage to Mud Slough is the SLD (Fig. 4). The SLD enters Mud Slough downstream of the Gun Club Road sampling site. By measuring the water quality at Site A (the entrance to the bypass) and Site B (near the exit of the bypass) we can determine the importance of agricultural drainage to water quality in the Mud Slough tributary and determine how the water quality changes during passage down the SLD. SLD samples were collected at both Site B and at check 2 on the SLD (Site B-gate) during this study (Fig. 4). Site B-gate is approximately 2 miles from Site B or about 7% of the total length of the bypass portion of the drain. Samples collected at the two sites were not significantly different and are combined for this paper. Comparison of SLD data (Site B and Site B-gate) with Mud Slough at Gun club Road data allows us to compare and contrast the importance of managed wetlands and agriculture to water quality in Mud Slough.

Salt Slough represents a mixed drainage influenced by both agriculture and wetlands. Samples were collected from Salt Slough at Wolfsen Road bridge and at Highway 165 (Fig. 4). Between these two points, the slough is bordered mostly by wetlands. The San Luis National Wildlife Refuge both diverts and returns water to Salt Slough between Wolfsen Road and Highway 165. These sample locations were chosen to

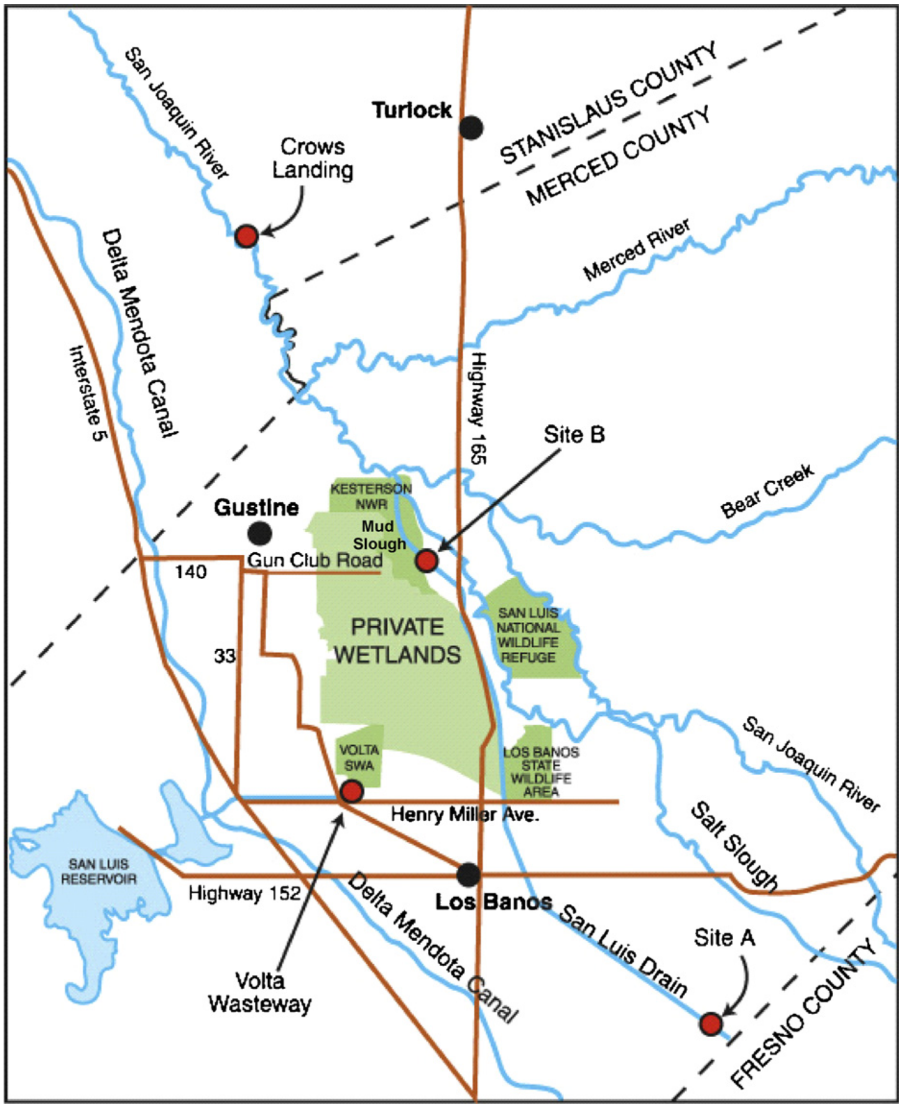

Fig. 3 – Map of the study region. Site A (the grassland bypass entrance to San Luis drain) and Crows Landing represent the most southern and northern sampling sites discussed in this paper.

differentiate the influence of the wildlife refuge from upstream sources of drainage.

The Mud Slough near Gustine monitoring station is situated downstream from the confluence of the SLD and Mud Slough (Fig. 4). Salt Slough and Mud Slough enter the SJR north of our study area. The first monitoring station on the SJR downstream of Salt and Mud Sloughs is Crows Landing (Fig. 3). To place the results of our study in the context of the larger

Table 1 – Location of sampling stations discussed in this paper

Site name	Latitude	Longitude	USGS site code
Site A on the San Luis drain[a]	35°57.883′	12°40.133′	11,262,890
Volta Wasteway at Ingomar Grade	37°06.317′	120°56.186′	–
Salt Slough at Wolfsen Road	37°12.533′	120°48.775′	–
Site B-gate on the San Luis drain	37°12.944′	120°51.098′	–
Mud Slough at Gun Club Road	37°13.887′	120°53.954′	–
Site B on the San Luis drain[b]	37°14.449′	120°52.914′	11,262,895
Salt Slough at state road 165	37°14.876′	120°51.116′	11,261,100
Mud Slough near Gustine	37°15.750′	120°54.333′	11,262,900
Crows Landing	37°25.917′	121°00.700′	11,274,550

[a] Entrance for the grassland bypass area drainage.
[b] Exit of the grassland bypass area drainage.

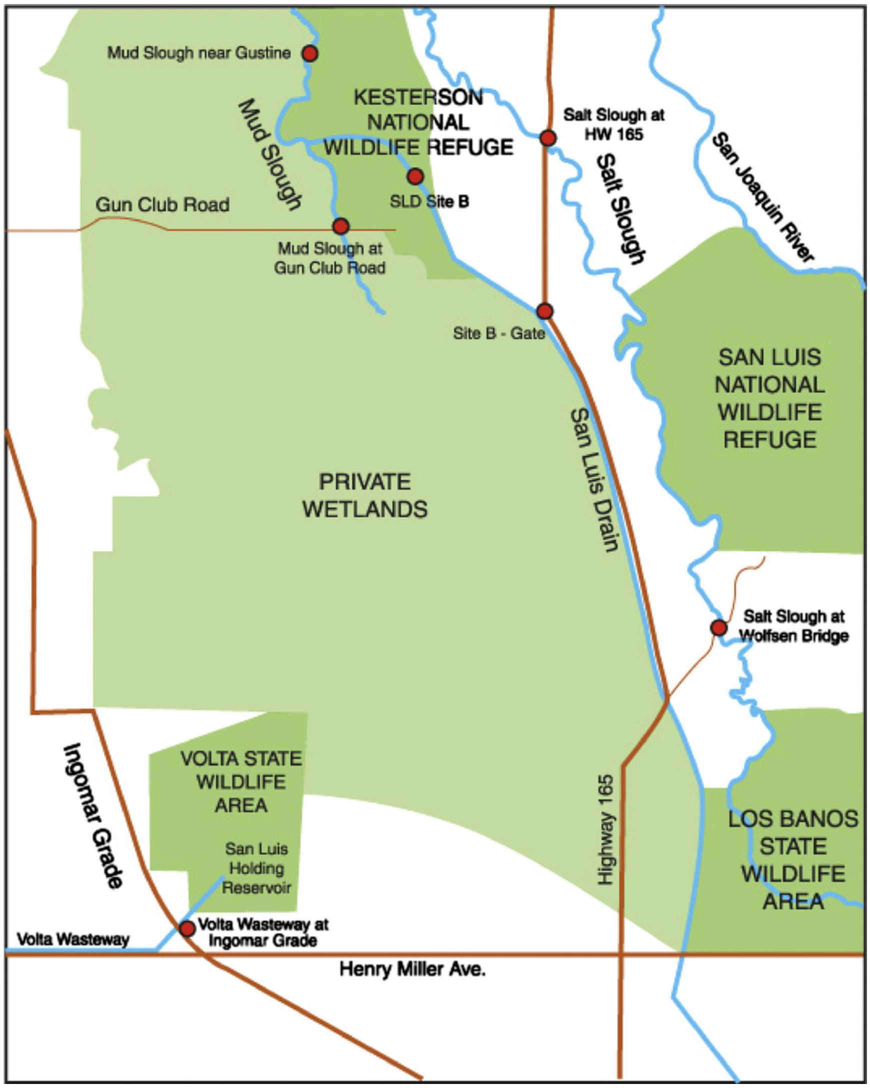

Fig. 4 – Map of sampling sites for agricultural and wetland drainage discussed in this paper. Site A and Crows Landing on the San Joaquin River are outside of map area (see Fig. 3).

river system, data collected in this study was compared to data collected by the RWQCB at Mud Slough near Gustine and Crows Landing.

2.3. *Sample collection and analysis*

Water samples were collected in liter glass bottles, placed on ice immediately, and kept at 4 °C until analyzed. All analyses were run within the allowed holding time for a refrigerated sample as described in standard methods (SMs) (American Public Health Association, 2005). Total BOD, carbonaceous biochemical oxygen demand (CBOD), and nitrogenous biochemical oxygen demand (NBOD) were measured according to SM 5210B. Total organic carbon (TOC) and dissolved organic carbon (DOC) were measured by SM 5310 A, the combustion infrared method, using an Apollo 9000-HS TOC analyzer (Teckmar-Dohrmann, Cincinnati, OH). Ammonia was quantified by the Nessler method. Orthophosphate and total phosphate were quantified by the ascorbic acid method (adapted from SM 4500-P-E). Ammonia, total phosphate and orthophosphate were analyzed using reagents purchased from HACH Co. (Loveland, CO). Total suspended solids (TSS) and volatile suspended solids (VSS) were analyzed by SM 2540 D and E, respectively. Chlorophyll *a* and pheophytin *a* were extracted and analyzed by spectrophotometric determination (SM 10,200H). Measurements for chlorophyll *a* and pheophytin *a* were combined and are reported as ‘‘algal pigments.’’

2.4. *Data analysis*

Data collected between 16 July and 4 October, 2001 are presented in this paper. Loads are calculated by multiplying concentration times the average daily flow from the day of sampling and are expressed as kg/day. Flow data was supplied by a number of sources including the USBR, LBNL, and local water agencies. Statistical analysis was conducted using Excel 97 (Microsoft Corp.). Correlation (*r*) coefficients were calculated using the linear, least-squares method.

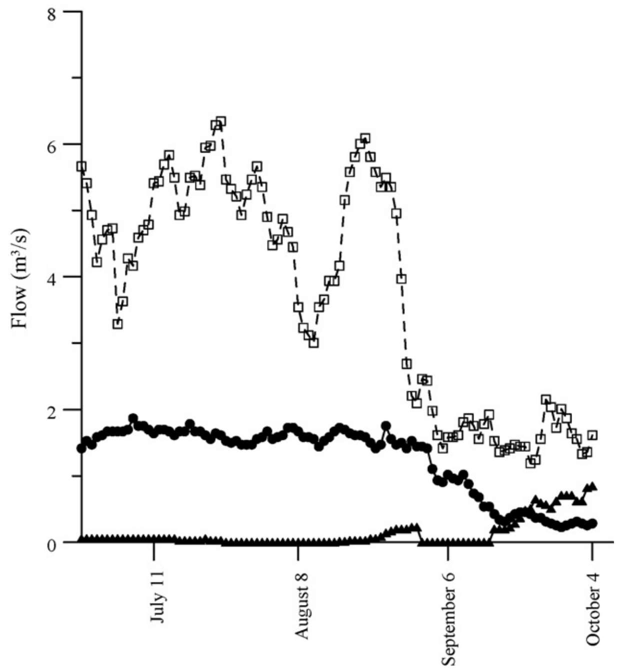

Fig. 5 – Average daily flow as a function of time for the three major drainages of the Grasslands region between 13 June and 4 October, 2001. Site B on the San Luis drain (●), Salt Slough at Highway 165 (□) and Mud Slough at Gun Club Road (▲).

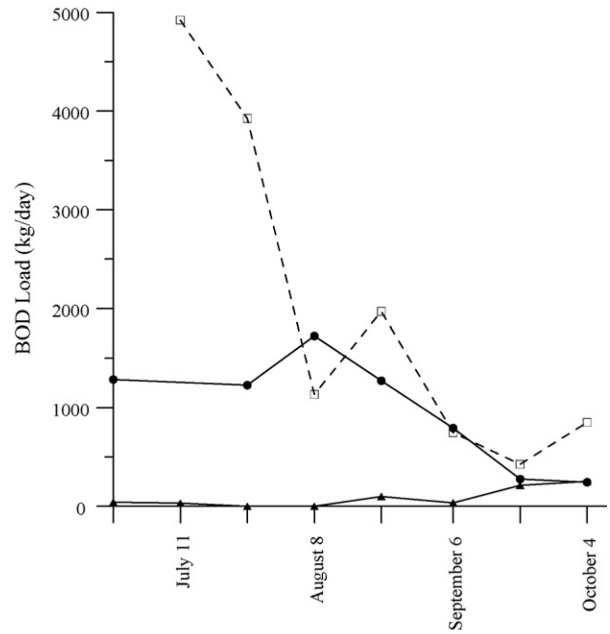

Fig. 6 – BOD_{10} loading as a function of time for the three major drainages of the grasslands region between 13 June and 4 October, 2001. Site B on the San Luis drain (●), Salt Slough at Highway 165 (□) and Mud Slough at Gun Club Road (▲).

3. Results and discussion

3.1. *Comparison of sources of BOD and algae in the Grassland Watershed*

The first objective of this research was to identify sources of BOD and algae in Salt and Mud Sloughs. During the summer, flows from wetland sources were low (Mud Slough at Gun Club Road) and agricultural sources were high (Salt Slough at Highway 165 and Site B). Examination of the seasonal flow pattern (Fig. 5) shows that wetland flows are low during the summer and only increase in September, during the flood-up period. Agricultural flows were highest during the summer irrigation period and dramatically decline at the end of the growing season (Fig. 5). Flows from Salt Slough are approximately three to four times flows exiting the SLD.

BOD loads from Salt Slough, Mud Slough and the SLD also vary seasonally (Fig. 6). BOD load from the wetlands increases as flood-up begins in September. Seasonal variation in BOD loading from the SLD appears to be related to algal growth in the drain (see below). Salt Slough had high BOD loads earlier in the summer and exhibited a consistent downward trend over the study period. Salt Slough carries drainage from both wetlands and agricultural areas, but the seasonal flow pattern suggests that the flow in the slough is predominantly agricultural drainage (Fig. 5).

Table 2 presents the average flows and loads measured at the three major regional discharges investigated in this study. Due to the low flows, managed wetlands contribute an overall lower loading of BOD, algae (chlorophyll *a* or algal pigments) and other measured constituents than agricultural sources from June to October (Table 2). Salt Slough has the highest flows and has the highest BOD, TSS, and orthophosphate loading of the three drainages. Site B is unusual in that it has twice the algae load of Salt Slough, despite having one-third the flow. On a flow basis, Site B is disproportionately lower in orthophosphate and TSS and higher in BOD than Salt Slough.

3.2. *Importance of Mud Slough and Salt Slough to BOD loads observed in the SJR*

In order to examine our results in the context of the overall water quality of the SJR, we compared our data to data collected at two sampling stations downstream of our study area. In 2001, the RWQCB only collected samples at these sites between 11 July and 20 September . Using the RWQCB BOD_{10} data, we calculated the relative contribution of our sample stations to BOD loading observed at Mud Slough at Gustine and Crows Landing.

Between 11 July and 20 September, discharge from the SLD (Site B) accounted for over 90% of the BOD loading observed at Mud Slough near Gustine (Table 3). This BOD contribution from the SLD is disproportionate to the amount of flow entering Mud Slough, even given the inherent uncertainty of the BOD analysis. A mass balance on the flows in Mud Slough suggests that our sampling stations do not account for approximately 20% of the flow from the region (Table 3). This is consistent with observations that two tributaries of Mud Slough, S-Lake drain and Hollow Tree drain, have flow during the summer. These streams drain wetland areas and enter Mud Slough below the Gun Club Road sampling station. These

Table 2 – Loading measured at the three major drainages of the grassland region between 13 June and 4 October, 2001

Sample location	Flow (m^3/s)	NH_4-N (kg/day)	BOD_{10} (kg/day)	$CBOD_{10}$ (kg/day)	Chlorophyll *a* (kg/day)	Algal pigments (kg/day)	o-PO_4 (kg/day)	TSS (kg/day)	VSS (kg/day)
Mud Slough at Gun Club Road	0.2 ± 0.3 (*n* = 9)	9.1 ± 14 (*n* = 7)	84 ± 97 (*n* = 8)	66 ± 79 (*n* = 8)	0.2 ± 0.3 (*n* = 7)	0.4 ± 0.6 (*n* = 7)	31 ± 32 (*n* = 5)	191 ± 308 (*n* = 6)	121 ± 218 (*n* = 6)
San Luis drain discharge (Site B)	1.2 ± 0.5 (*n* = 9)	87 ± 83 (*n* = 5)	973 ± 516 (*n* = 8)	880 ± 459 (*n* = 8)	8.5 ± 7.5 (*n* = 10)	9.8 ± 8.2 (*n* = 10)	7.3 ± 9.7 (*n* = 5)	4774 ± 2,100 (*n* = 8)	2400 ± 1,499 (*n* = 8)
Salt Slough at Highway 165	3.9 ± 1.4 (*n* = 9)	160 ± 249 (*n* = 5)	1996 ± 1749 (*n* = 7)	1049 ± 609 (*n* = 7)	4.6 ± 2.6 (*n* = 5)	5.7 ± 3.3 (*n* = 5)	240 ± 297 (*n* = 4)	52,311 ± 40,214 (*n* = 5)	12,516 ± 13,902 (*n* = 5)

Mean ±S.D. and sample population (*n*)

Table 3 – Flow and BOD_{10} loading at tributaries to Mud Slough expressed as a percent of the average flow and loading at Mud Slough at Gustine[a]

Sample location	% Flow	% BOD_{10} load
Mud Slough at Gun Club Road	5.7	6.6
Site B	74.6	92.4
Mud Slough near Gustine[a]	100	100
Balance[b]	19.7	1.0

Data for 11 July–20 September, 2001 only (*n* = 6).
[a] Mud Slough at Gustine BOD_{10} data provided by the RWQCB.
[b] Flow and loading at Mud Slough near Gustine not accounted for by flows from Mud Slough at Gun Club Road and Site B.

drainages do not appear to contribute significant BOD to Mud Slough (Table 3).

Drainage flows and BOD loads from the Grassland Watershed were compared to flows and BOD loads measured at Crows Landing on the SJR (Table 4). During the period 11 July–20 September, only a small proportion of the BOD at Crows Landing can be accounted for as coming from wetlands draining to Mud Slough. The SLD conveys a disproportionately high amount of BOD (15%) compared to flow (11%), but overall the grassland region appears to have a balance between flow and BOD contribution (Table 4). This result suggests that there are other sources of BOD above Crows Landing that contribute to the BOD load in the SJR.

Based on the data presented here, it can be concluded that managed wetlands draining to Mud Slough do not present a significant source of BOD or algae to the SJR during June–August. However, flow, BOD and algae loads from these wetlands increase in September and October (Figs. 5 and 6). The impact of these discharges on late season oxygen deficits in the SJR needs further investigation.

Agricultural drainage was found to contain significant amounts of BOD. The agricultural drainage in the region originates largely from subsurface drains and therefore would not be expected to have significant concentrations of

Table 4 – Flow and BOD_{10} loading at different sampling stations expressed as a percent of the average flow and loading at Crows Landing[a]

Sample location	% flow	% BOD_{10} load
Mud Slough at Gun Club Road	0.8	6.6
Site B	10.9	15.3
Mud Slough at Gustine[a]	14.5	17.3
Salt Slough at Highway 165	31.0	25.8
Mud Slough at Gustine[a] and Salt Slough at Highway 165 combined	45.5	43.1
Crows Landing	100	100

Data for 11 July–20 September, 2001 only (*n* = 6).
[a] Mud Slough at Gustine and Crows Landing BOD_{10} data provided by the RWQCB.

Table 5 – Changes in water quality between Volta Wasteway and Mud Slough at Gun Club Road

Sample location	TOC[a] (mg/L)	NH_4-N[b] (mg/L)	BOD_{10} (mg/L)	$CBOD_{10}$[b] (mg/L)	Chlorophyll *a* (μg/L)	Algal pigments[b] (μg/L)	o-PO_4[b] (mg/L)	TSS[b] (mg/L)	VSS (mg/L)
Volta Wasteway	7.1 ± 4.7 (n = 9)	0.2 ± 0.2 (n = 7)	8.5 ± 6.9 (n = 8)	5.1 ± 3.36 (n = 8)	14.2 ± 14.6 (n = 7)	22.7 ± 19.1 (n = 7)	0.39 ± 0.14 (n = 5)	31.3 ± 19.8 (n = 6)	12.9 ± 10.4 (n = 6)
Mud Slough at Gun Club Road	12.6 ± 3.0 (n = 9)	0.6 ± 0.6 (n = 7)	11.1 ± 5.7 (n = 8)	7.6 ± 3.4 (n = 8)	27.9 ± 24.0 (n = 7)	38.9 ± 24.3 (n = 7)	2.19 ± 2.58 (n = 5)	16.1 ± 7.0 (n = 6)	12.5 ± 8.8 (n = 6)

Average values ±S.D. for samples collected between 13 June and 4 October, 2001

[a] Significantly different at $\alpha = 0.05$, Student's *t*-test.

[b] Significantly different at $\alpha = 0.10$, Student's *t*-test.

Table 6 – Changes in Salt Slough water quality between Wolfsen Road Bridge and Highway 165

Sample location	TOC[b] (mg/L)	NH_4-N (mg/L)	BOD_{10}[b] (mg/L)	$CBOD_{10}$[a] (mg/L)	Chlorophyll *a* (μg/L)	Algal pigments (μg/L)	o-PO_4 (mg/L)	TSS (mg/L)	VSS (mg/L)
Salt Slough at Wolfsen Road Bridge	7.7 ± 1.1 (n = 6)	0.5 ±0.4 (n = 5)	8.4 ± 3.0 (n = 7)	5.4 ± 1.3 (n = 7)	16.5 ± 12.2 (n = 6)	22.9 ± 14.3 (n = 6)	0.72 ± 0.33 (n = 4)	119 ± 55.4 (n = 5)	29.4 ± 27.3 (n = 5)
Salt Slough at Highway 165	6.6 ± 1.1 (n = 7)	0.5 ± 0.5 (n = 5)	5.8 ± 2.7 (n = 7)	3.5 ± 0.9 (n = 7)	20.5 ± 8.0 (n = 5)	25.2 ± 8.4 (n = 5)	0.86 ± 0.43 (n = 4)	126 ± 65.9 (n = 5)	29.8 ± 26.6 (n = 5)

Average values ±S.D. for samples collected between 13 June and 4 October, 2001.

[a] Significantly different at $\alpha = 0.05$, Student's *t*-test.

[b] Significantly different at $\alpha = 0.10$, Student's *t*-test.

phosphate, BOD, algae, or TSS upon being pumped from tile-drain sumps. However, it is apparent from this study that drainage entering the SLD at Site A has significant amounts of phosphate, algae solids, and BOD (Table 7). The sources of phosphate, TSS, and possibly some BOD is most likely plant debris and sediments from the unlined drainage ditches used to convey the sub-surface tile drainage to the point of entry to the SLD (Site A). Phosphate concentrations are high enough and residence times are long enough in the surface drainage ditches to allow significant algal growth, which is contributing BOD. For example, travel time from an individual sump discharge to the SLD can take from a few hours to several days, depending on local drainage management and the position of the drainage sump in the watershed. Opportunities may exist to reduce TSS and BOD load by altering ditch management practices or by controlling algal growth. Changes made to reduce BOD production in agricultural drainage could have a beneficial effect on the water quality of the SJR.

3.3. *Changes in water quality between sampling points*

The second objective of this study was to examine water quality changes that occur between upstream and downstream sample points for each drainage system. Table 5 reports changes in water quality that occur as water is used in wetland management. Water enters the wetland areas via the Volta Wasteway and flows north and west, eventually exiting at Mud Slough and other drainages (Fig. 4). Table 5 compares the quality of the water at Volta Wasteway to the water quality at Gun club Road. The drainage water in Mud Slough at Gun Club Road was significantly higher in TOC, ammonia, $CBOD_{10}$, TSS, algal pigments, and orthophosphate than the water entering the wetland at Volta Wasteway at the $\alpha = 0.1$ level or better. BOD and chlorophyll *a* concentrations were slightly elevated at Mud Slough, but the differences we not significant (Student's *t*-test, $\alpha = 0.1$).

In permanent wetlands, BOD production can be attributed to well understood processes, such as algal growth, leaching of organic carbon from live and decaying plant material, and ammonia production from anaerobic sediments. In seasonal wetlands, that are dry throughout the summer months, processes that influence BOD production are less well understood. Soils will become oxidized during the dry season and residual organic matter from the previous wet period will stabilize, so soils in seasonal wetlands may not contribute much BOD to the water column. A major source of BOD in seasonal wetlands is likely to be the standing crops of dry-land plants that die and decay once they are flooded. Initial flooding may result in a large flush of BOD from the system. The temporal pattern of BOD production in seasonal wetlands could be important to management of the dissolved oxygen TMDL and needs to be better understood.

The TOC, BOD_{10}, and $CBOD_{10}$ concentration of Salt Slough decreased between Wolfsen Road Bridge and Highway 165 (Table 6). Other water quality parameters did not significantly change between the two sampling points. Flow at Wolfsen Road is not statistically different from flow at Highway 165, however the San Luis refuge does have an operational pumping station on Salt Slough between these points. It is possible that some water quality changes between Wolfsen Road Bridge and Highway 165 may be associated with diversions from the slough during the summer months. The results demonstrate that water quality is poor in Salt Slough, but do not indicate that the National Wildlife Refuge is impacting water quality in this stretch of the slough.

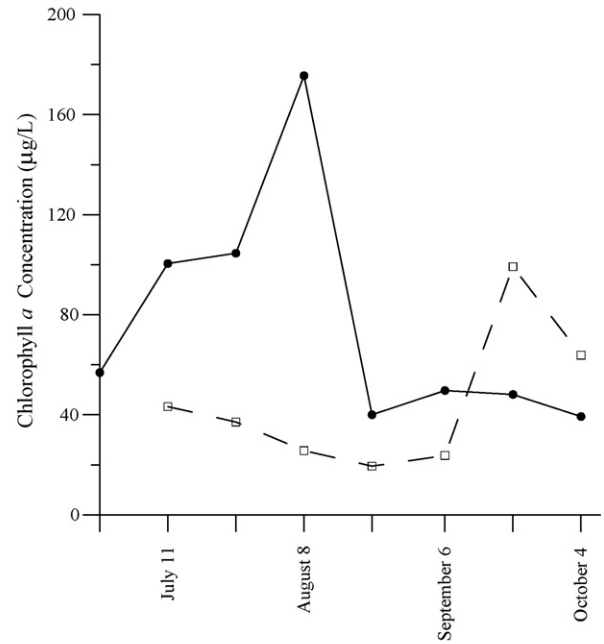

Fig. 7 – Chlorophyll *a* concentration as a function of time for the inlet (Site A, □) and outlet (Site B, ●) of the San Luis drain between 13 June and 4 October, 2001.

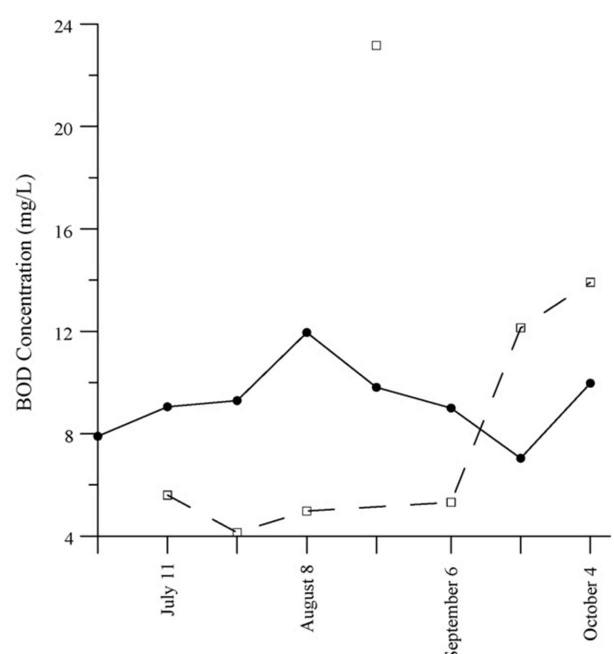

Fig. 8 – BOD_{10} concentration as a function of time for the inlet (Site A, □) and outlet (Site B, ●) of the San Luis drain between 13 June and 4 October, 2001.

Table 7 – Changes in water quality between the entrance and exit of the San Luis drain

Sample location	TOC[b] (mg/L)	NH_4-N (mg/L)	BOD_{10} (mg/L)	$CBOD_{10}$ (mg/L)	Chlorophyll a[b] (μg/L)	Algal pigments[b] (μg/L)	o-PO_4[b] (mg/L)	TSS[a] (mg/L)	VSS (mg/L)
Site A	8.5 ± 2.0 (n = 7)	1.0 ± 0.6 (n = 5)	9.9 ± 7.0 (n = 7)	8.7 ± 5.6 (n = 7)	44.6 ± 28.4 (n = 7)	50.9 ± 26.0 (n = 7)	0.32 ± 0.33 (n = 4)	141 ± 142 (n = 5)	24.5 (±15.4)n = 5
Site B	7.4 ± 1.1 (n = 10)	0.8 ± 0.7 (n = 7)	9.3 ± 1.5 (n = 8)	8.4 ± 1.4 (n = 8)	70.0 ± 44.9 (n = 10)	81.0 ± 47.8 (n = 10)	0.07 ± 0.07 (n = 5)	41.2 ± 8.3 (n = 8)	20.9 (±9.2)n = 8

Average values ±S.D. for samples collected between 13 June and 4 October, 2001.
[a] Significantly different at α = 0.05, Student's t-test.
[b] Significantly different at α = 0.10, Student's t-test.

Table 8 – Correlation between BOD_{10} and individual water quality measurement believed to contribute to BOD_{10}

Water quality parameter	n	Correlation with BOD_{10} (r)
BOD_{10} (mg/L)	44	1.000
TOC (mg/L)	44	0.500
DOC (mg/L)	44	0.406
Chlorophyll a (μg/L)	40	0.307
Pheophytin a (μg/L)	40	0.235
Chlorophyll a + pheophytin a (μg/L)	40	0.354
Ammonia-N (mg/L)	33	0.097
TSS (mg/L)	33	−0.154
VSS (mg/L)	33	−0.051

All data collected between 13 June and 4 October, 2001.

3.4. *Algal growth and BOD production in the San Luis drain*

The SLD is high in nutrients, open to the sunlight, and is therefore potentially a conducive environment for algal growth. Chlorophyll a concentrations at Sites A and B are plotted as a function of time in Fig. 7. During much of the summer there is a dramatic increase in chlorophyll a concentration between the entrance and exit of the drain. BOD often increases during passage down the drain as well during the period corresponding to increased algae production (Fig. 8). However, there was 1 day during mid-summer where the BOD at Site A was higher than the BOD at Site B (Fig. 8). This high BOD was associated with a slug of brownish-green water flushed into the SLD from upstream. The pattern of deteriorating water quality changes at the end of the irrigation season. After September, there is a net reduction in BOD and chlorophyll a between the two sample sites on the SLD.

A comparison of all the data for Sites A and B revealed that there is a significant difference in TOC, orthophosphate, chlorophyll a, algal pigments, and TSS concentration between the two stations (Table 7). Orthophosphate removal is dramatic, and suggests that algal growth in the SLD may at times become phosphate limited. Although the BOD change overall was not significant (Table 7), due to occasional spikes of high BOD water entering the drain and late season influent BOD increases (Fig. 7), the seasonal pattern in BOD suggests that algal growth is contributing BOD discharged at Site B. If phosphate could be removed at the head of the drain or the drain could be shaded, it might be possible to stop the algal growth in the drain. Installing engineered controls on algal growth in the SLD could be one approach to limiting BOD and algal production in the region.

3.5. *Characteristics of BOD in the Grassland Watershed*

In order to evaluate BOD control strategies for the region, it is important to gain an understanding of what constituents of the water contribute to oxygen demand. We tested individual water quality parameters for their correlation with BOD_{10} (Table 8). BOD_{10} has the highest correlation with TOC and DOC, followed by chlorophyll a. Ammonia-N did not correlate with BOD_{10}, which suggests that ammonia is a less important component of BOD_{10} than either TOC or algae in this system. This result suggests that BOD management in the region should prioritize control of algal production over control of ammonia discharges. Additionally, point and non-point source discharges of BOD need to be further characterized to determine how much of the biodegradable organic carbon is of algal origin and how much actually comes from other sources.

4. Conclusions

- Wetlands and irrigated agriculture both negatively impact water quality in the watershed. Drainage from wetland areas has a higher BOD concentration than drainage from agriculture areas. However, agricultural drainage flows are higher, therefore agricultural drainage is contributing more BOD load to the SJR during June through September.
- The concentrations of organic carbon and phosphate in water exiting the wetlands is measurably higher than in the water supplied to the wetlands. The processes that impact water quality in seasonal wetlands are not well understood and warrant further investigation.
- Algal growth in the SLD is an important source of algal discharge in the region. The configuration of the SLD offers opportunities for algal control that could reduce the BOD and algal load from the entire region.
- Although previous studies have shown that Mud Slough and Salt Slough tributaries are responsible for a disproportionate amounts (in relation to flow) of several inorganic pollutants entering the SJR, overall these tributaries are not contributing a disproportionate amount of BOD entering the river.

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